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6. AUTHOR(S)
D. V. Averin, S. Han, K. K. Likharev, J. E. Lukens, and V. K. Semenov

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Stony Brook University
Stony Brook, NY 11794

The University of Kansas
Lawrence, KS 66045
(subcontractor)

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE, Attn: Dr. Harold Weinstock
875 N. Randolph St., Suite 325
Arlington, VA 22203-1768

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14. ABSTRACT

This is a final performance report on a DURINT project, which summarizes its main achievements, including:

- the design of sophisticated instrumentation for the control and measurements of superconductor flux qubits,
- the refinement of qubit fabrication technology,
- the demonstration of coherent operation of qubits both in frequency and time domain, and
- the design and analysis of new superconductor devices for processing and measurement of quantum information.

Despite several challenges still faced by superconductor-based quantum computing, the project has been a major step toward addressing the still unsolved problems of the field.

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A. EXECUTIVE SUMMARY

1. Objectives:

The main objectives of this project have been as follows:

- to develop a physics background for scalable solid-state quantum computing,
- to determine fundamental limits on coherence in Josephson-effect qubits, and
- to demonstrate coherently interacting qubits and (possibly) quantum logic gates.

Our main approach was to work toward Josephson-junction flux qubits controlled using either external video pulses (Stony Brook) and rf pulses (KU). The Stony Brook group also worked on the development of special SFQ circuits for future advanced quantum computing circuits. The project also included a substantial theoretical effort directed at both the development of new ideas for quantum computing and providing support for the experimental work.

2. Major accomplishments:

(i) Qubit experiments at Stony Brook (Co-P.I: J. Lukens)

As with all groups using Josephson effect qubits, our results were severely limited by the presence of unexpected 1/*f* flux noise, which was particularly severe in our large area qubit. The discovery of this noise has forced us to change the focus of our work to an investigation of single qubit noise properties as they affected coherence.

The main accomplishments and results of this effort are as follows:

- The design and construction or a sophisticated apparatus for the measure and control of flux qubits that permitted high speed control and readout of the qubit at 5mK while reducing the effect of the external environment to negligible levels.
- The development and refinement of technology for the fabrication of qubits and related circuitry using a niobium trilayer process.
- Measurement of junction properties related to decoherence such as subgap leakage and 1/*f* critical current noise. The measured 1/*f* noise spectral density of junctions fabricated at Stony Brook is about two orders of magnitude less than that commonly reported.
- The demonstration of coherent operation of a single qubit through the measurement of Rabi oscillations and Ramsey fringes and the subsequent extraction of related decoherence times associated with various noise processes.

The design and layout of our qubit along with the associated on-chip control and readout circuitry are shown in Fig. 1. In addition to the qubit at the lower center of the figures, control coils for ϕ_{xdc}, which controls the coupling between qubit states and ϕ_x, which controls the level spacing of the qubit are shown. The top parts of Fig. 1a and Fig. 1b show the schematic and micrograph of the magnetometer used for high speed readout of the state of the qubit. These dual controls allow us to operate the qubit in the flux basis as originally planned or in what has come to be know as the phase basis using the two lowest levels in one fluxoid well (Fig.2) .

The results presented below use basis states in the same well, shown in Fig. 2, since the effect of flux noise on these states is about 100x less than for two levels in different wells. The in-well level spacing is about 20 GHz or 1K. The measured T_1 for these level is 20 ns. Figure 3, showing resonant occupation of |1> vs. level spacing, illustrates the various decoherence processes such as two level fluctuators (seen as gaps in the occupation) and cavity resonances (bright horizontal line). Finally Fig. 4 shows Rabi oscillations obtained for a bias away from any of the pathologies seen in Fig. 3. Here the Rabi frequency is proportional the microwave amplitude as expected (inset) and the decay time is 16.6 ns. This is consistent with the measure T_1 above plus and additional decay at the Rabi frequency with T_{Rabi} = 25 ns. These resonant data are not affected by the flux noise. However addition measurement of Ramsey fringes, off resonant Rabi oscillations and resonant tunneling peaks between wells are. All give a low frequency flux noise consistent with an rms detuning of $\sigma = 2.2 \times 10^8 s^{-1}$. This is far too large for successful operation of complex gates. So, further development of these qubits will require an understanding and significant reduction of this noise.

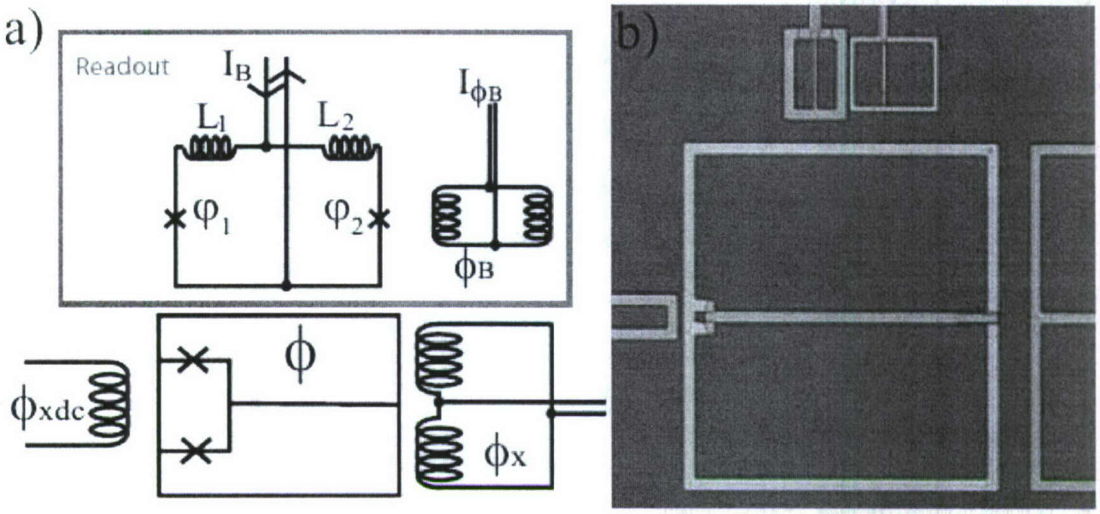


FIG. 1: a) Schematic and b) micrograph of rf SQUID qubit, readout magnetometer and flux control coils.

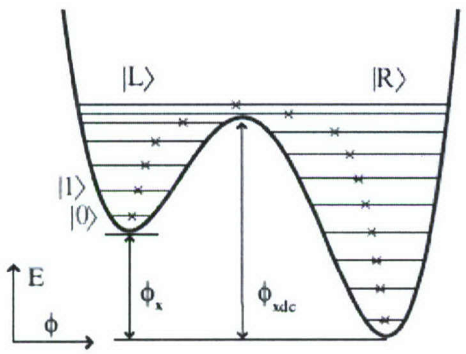


FIG. 2: The potential diagram of an rf-SQUID at a β = 1.32 and φ_x = 0.505 showing localized energy levels and the corresponding value of mean flux

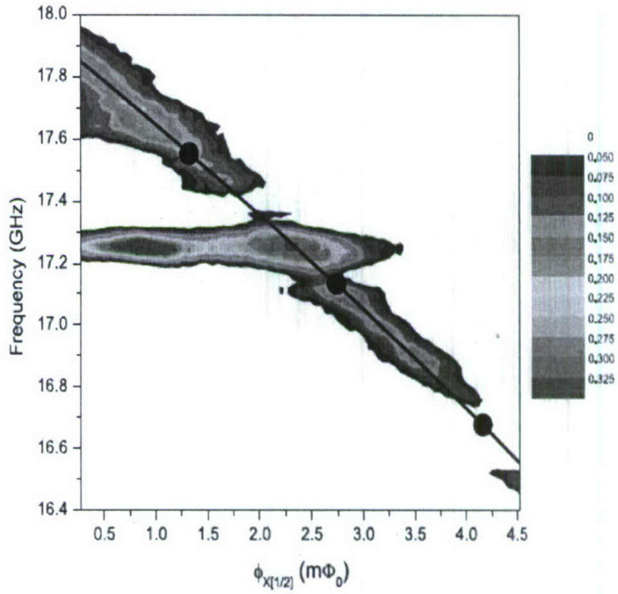


FIG. 3: The measured occupation of the excited state after a long microwave pulse expressed as color contours (blue being lowest and red being the highest) as function of both frequency and φ_x. The solid lines are calculations of the energy level spitting between consecutive eigenstates states in the same well for β = 1.30, L = 190 pH and C = 209.7 fF.

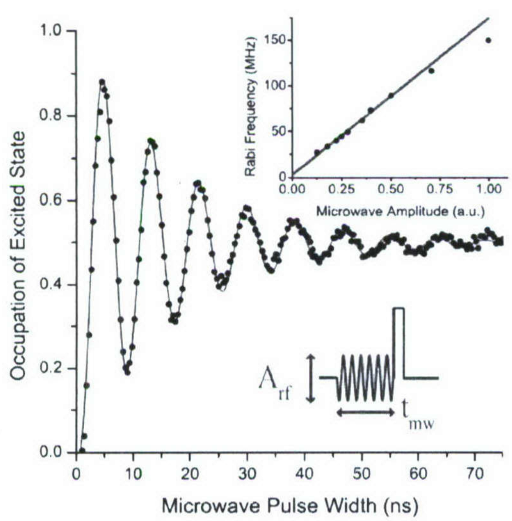


FIG. 4: The occupation of the excited state as a function of the length of the microwave pulse demonstrating Rabi oscillations. The line is a numerical solution to the Bloch equations exactly on resonance with f_{Rabi} = 119MHz and decay time T_2 = 16.6ns. The inset shows the Rabi frequency as a function of amplitude of applied microwaves in arbitrary units. The line is a linear fit to the lower microwave amplitude data.

(ii) Qubit experiments in U. Kansas (Co-P.I.: S. Han)

What follows is a list of our major accomplishments of this effort:

- For the first time we observed Rabi oscillation in a Josephson tunnel junction phase qubit. The lower limit of decoherence time, obtained from best-fit of the data to the theoretical prediction of an unstable system undergoing Rabi oscillations, is about 5 μs, which includes the effects of both relaxation and dephasing.

- By measuring flux noise via inhomogeneous broadening of spectral linewidth and/or the width and shape of macroscopic resonance tunneling peaks in superconducting flux qubits with inductance ranging from less than 30 pH to greater than 1 nH, with different types of loop configurations (e.g., magnetometer, 1^{st} order gradiometer, 2^{nd} order gradiometer), and coupling strength to external bias circuitry and/or environment we were the first to unambiguously show that low frequency flux noise is the dominant mechanism of decoherence in RF SQUID qubits and the source of the noise is definitely generated on-chip – from defects in materials surrounding and/or as a part of the qubit.(e.g., tunnel barrier). Our result, based on measurement from five flux qubits fabricated by Nb trilayer process, shows that the total flux noise is proportional to inductance of the qubit (~0.9 mΦ_0/nH).

- In collaboration with a *D-Wave Systems* group we experimentally observed that at degeneracy point an RF SQUID qubit has minimum tunneling rate (in contrast to the common belief that the rate should be maximum at degeneracy point). This observation confirmed a theory on MRT developed by Amin and Averin on macroscopic quantum tunneling. We also used it to quantify LFFN in our flux qubits.

- We have carried out the measurement of T_1 time between different fluxoid states of an RF SQUID (and other qubit parameters important for the three-level operation mode, including the rf-to-qubit coupling constant) using time-resolved measurements of the top level rf-excitation from one of the bottom levels, followed by its inelastic relaxation into another lower state. This low level of relaxation, T_1 ~ 4 μs, is lower than the expected dephasing rate due to other sources.

- We measured the bias and temperature dependence of T_1 time between fluxoid states that have clockwise and counterclockwise persistent current. The result clearly shows that at finite temperature the simple two-level approximation breakdown and one must take into account occupation probability of excited states.

- We have proposed a three-level flux qubits as the possible option for quantum computing. In this option, switching between two flux states, localized near the corresponding wells of the qubit potential, is carried out with two (rather than one) rf drives. One of the drives Rabi-transfers the qubit state to the third, upper energy level (located above the potential barrier), while the second drive competes the coherent transfer to another lower state. The main advantage of this approach is that the lower, working energy levels (0 and 1) can be now hidden deeper inside their potential wells, thus reducing the rate γ_{10} of the parasitic incoherent transfer between the states.

- We have made the first proposal to use superconducting qubits coupled to microwave cavity for quantum information processing and to study fundamental physics such as the strong-coupling limit of cQED. Samples have been designed and fabricated. Preliminary measurement was carried out. The result is very encouraging. For example, measured quality factor of coplanar waveguide is greater than 10^5.

- We have demonstrated macroscopic quantum tunneling in intrinsic Josephson junctions made from Bi-2212 single crystal. Since Bi-2212 intrinsic junctions tunnel barrier conserves the lattice structure and chemical composition of the crystal it has much lower defect density than artificially engineered tunnel barrier. Therefore, it is expected to have much lower low frequency flux and charge noise which has plagued further development of superconducting qubits for quantum computation.

(iii) Theoretical work (Co-P.I.: D. Averin)

The main results obtained in this effort are as follows:

- *Design and theory of new devices:*

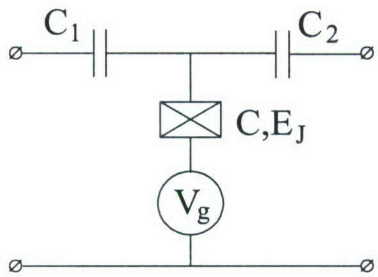


FIG. 5. The variable electrostatic transformer.

- We have suggested and calculated characteristics of a "variable electrostatic transformer (Fig. 5), a simple single-junction device that allows to control the strength of coupling between charge qubits by varying the quantum capacitance of a small Josephson junction. The ability to do this contradicted the commonly held view of impossibility to vary the coupling of charge qubit set by their geometric capacitance. After our work, quantum capacitance of Josephson junctions has found other applications, e.g., for measurements of charge qubits.

- We suggested the general notion of a quadratic quantum detector which possesses non-trivial quantum-information properties, e.g., can entangle qubits by measurement, and developed a simple error-correction scheme for superconducting qubits based on such a detector.

- We have developed the theory of quantum coherent oscillations in coupled qubits and their weak decoherence. The theory facilitated experiment on coupled charge qubits.

- *Quantum measurements of qubits.*

- We have developed the general theory of linear quantum measurements with mesoscopic detectors. The main conclusion of the theory is the existence of general relation, similar to the Heisenberg uncertainty principle, between the detector linear-response coefficients which determines the balance between the detector back-action dephasing of the measured system and acquisition of the information about the system. This relation shows how close the detector is to being quantum-limited.

- The linear measurement theory was extended beyond the linear regime for an important class of mesoscopic detectors, scattering detectors. This extension shows that the appropriate measure of the information acquisition rate is given by the Renyi entropy, not a more conventional Shannon entropy, and establishes the condition of the quantum-limited operation of a point-contact detector, the most universal detector for the quantum-dot qubits.

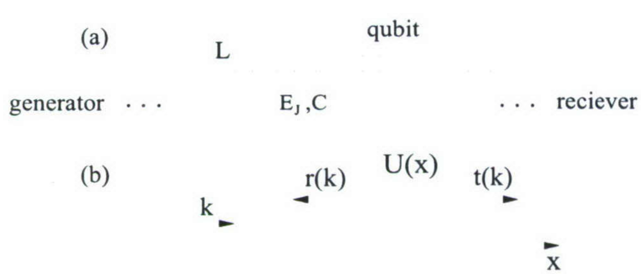


FIG. 6. Fluxon scattering detector.

- We have suggested the scattering detector based on the ballistic motion of fluxons in Josephson transmission lines (Fig. 6). The detector should combine short response time with quantum-limited sensitivity produced by its ability to shield the qubit from the resistor noise in SFQ parts of the circuit necessary for manipulation of individual fluxons.

- *Dynamics of qubit decoherence.*

The decoherence properties of practical qubits are dominated by the low-frequency noise which is not describable by the standard theory of weak decoherence. We have developed the appropriate theory [9] of low-frequency decoherence by classical noise. The theory predicts non-exponential decay of coherence, can be generalized to quantum noise, and used in further studies of the low-frequency noise in flux-based qubits.

(iv) SFQ/qubit systems (D. Averin, V. Semenov)

The work is this direction was focused on the analysis of challenges faced by interfacing of superconductor qubits with supporting superconductor circuits. These challenges may be separated into two groups.

- The first group of problems results from parasitic heating of qubits by energy dissipated in the support circuits. This problem is exacerbated by a dramatic degradation of thermal conductivities of most materials (especially dielectrics) at millikelvin temperatures, with thermal conductivity proportional to T^4 or T^6. This complication is partly eased by a ballistic mechanism of heat propagation is monocrystal dielectrics, such as silicon. We have developed several SFQ circuits with dramatically minimized energy dissipation which have allowed us to experimentally confirm the correctness of our understanding of the heat flow in superconductor integrated circuits operating at millikelvin temperatures. Figure 7 shows a layout of one of such circuit (a JJ comparator), and the measured width of its grey zone as a function of the sink temperature. The plot shows that above 0.3 K the effective electron temperature of the comparator follows the sink temperature, but cannot be reduced below 0.2 K.

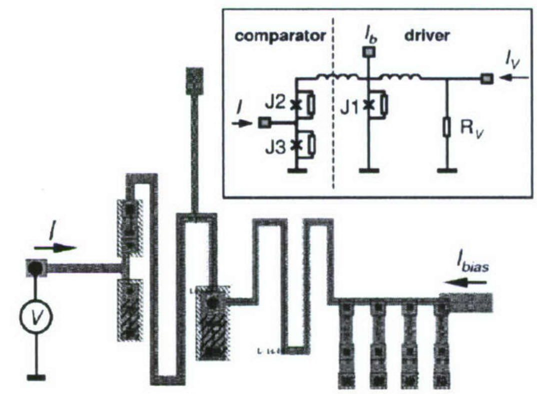
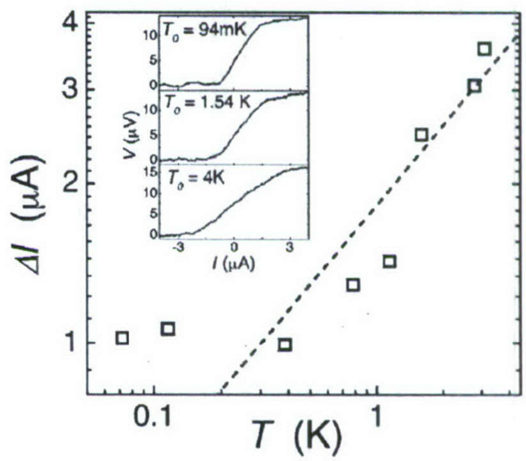


FIG. 7. Layout and equivalent circuit of the measured comparator.



- The second group of problem is caused by the direct back-action of the support electronics on qubits. We have shown that these problem could substantially decrease the decoherence time if the conventional, comparator-like SFQ readout circuits were used. We have suggested a so-called ballistic readout that allows the back-action to be reduced to fundamental limits defined solely by the quantum nature of the readout circuitry.

To summarize, we feel that though we could not achieve some project goals (e.g., demonstrate operational quantum logic gates), our work was a major step forward the understanding the prospects and problems of superconductivity-based devices and circuits for quantum information processing.

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C. PRESENTATIONS

J. Lukens' group

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D. Bennett, V. Patel, L. Longobardi, W. Chen and J. E. Lukens, Low Back-action Readouts for Flux Qubits, presented at ASC 2006.

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Wei Chen, Douglas Bennett, Vijay Patel and James Lukens, Losses in Nb Thin Films used for Qubit Fabrication, presented at the APS March Meeting 2007.

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L. Longobardi, D. Bennett, V. Patel, W. Chen and J. E. Lukens, rf-SQUID Qubit Readout using a Fast Flux Pulse, presented at ISEC 2007.

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